REPORT

Watercare Services Ltd

Central Interceptor - Vibration Assessment for Main Tunnels and Link Sewers

Report prepared for:

Watercare Services Ltd

Report prepared by:

Tonkin & Taylor Ltd

Distribution:

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July 2012

T&T Ref:27993

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Executive summary

Watercare Services are proposing to construct a new wastewater tunnel to collect flows from the Auckland isthmus and transfer them to the Mangere Wastewater Treatment Plant. It will be designed to provide future trunk sewer capacity to Central Auckland and reduce wet weather wastewater overflows.

Engineering and environmental studies have been undertaken to support the gaining of the necessary RMA approvals for the project. This includes a vibration assessment of effects of construction and operations of the project.

The principal works include construction of approximately 13 km of tunnels of around 4.5 m diameter and located up to 110 m below ground. This will be supplemented by a series of link sewers and connections to existing sewers. Other major works include access shafts of up to 35 m diameter for installation of the tunnelling equipment and a number of inground and above ground structures.

The main tunnel alignment will be constructed in East Coast Bays Formation rock (ECBF) and excavation is expected to be undertaken using an earth pressure balance tunnelling machine (EPBM). These have been used in similar geological conditions on other recent sewer tunnels in Auckland, including Rosebank and Hobson Bay Sewers.

Basalt rock from the Auckland volcanic field extends over parts of the tunnel routes and this will require excavation for shafts up to 25m in dimension and other underground structures. Work is expected to involve use of explosive charges and heavy rock breaking equipment to fragment the rock.

Where ECBF or more recent alluvial sediments are present, excavation will be by conventional construction plant but retention of the ground may involve use of heavy bored piling equipment and driven sheet piling.

An assessment of the level of vibrations generated by the equipment types has been undertaken including analysis of the expected rate of attenuation with distance from the sources. A review of the vibration criteria for physiological effects on people and potential for damage to structures has also been undertaken to provide recommended controls for the work. These have been used to determine the potential effects of transmitted vibration on people and properties from the construction activities and identify where mitigation measures are likely to be required. These will generally involve use of modified methods that reduce vibration levels but also include strengthening, isolation and temporary relocation.

The properties most likely to be affected have been determined and specific recommendations provided. A Construction Vibration Management Plan has been also recommended for the project to minimise discomfort and the effects on health as well as ensure risk of damage to structures is less than minor.

An assessment of the effects of vibrations of operation was carried out by monitoring several existing pump stations. The effects of these operations beyond the pump station structures was determined to be less than minor.

1 Introduction

1.1 Background

Watercare Services Ltd (Watercare) is planning to construct a new wastewater tunnel to collect wastewater flows from the Auckland isthmus area and transfer them across the Manukau Harbour to the Mangere Wastewater Treatment Plant (MWWTP). The Central Interceptor Project (the Project) arose out of the Three Waters Plan (2008) which identified the need to provide trunk sewer capacity to central Auckland to reduce wet weather wastewater overflows and provide capacity for growth.

The project extends across the Auckland isthmus from Western Springs in the north to the Mangere WWTP in the south. The general layout is shown on Figure 1.1 and the Drawing Set AEE-Main Series.

Watercare appointed an AECOM led team to progress the engineering and environmental studies to support the gaining of the necessary RMA approvals for the project. This vibration assessment forms one of a series of specialist environmental investigations commissioned by Watercare in 2011. It addresses the effects of vibrations of construction and operations of the main tunnel and link sewers. The effects of vibrations caused by construction of the Combined Sewer Overflows are addressed in a companion report. It is intended that this report provides technical input to supplement the AEE Report.

1.2 Methodology

The scope of work undertaken as part of this assessment is summarised below and described in detail in the following sections:

- briefing and site tour with Central Interceptor project team;
- review of concept designs including site construction yards and operation layouts;
- review of geotechnical information and assessment of ground conditions for excavation of shafts and tunnels;
- discussions with Central Interceptor project team to identify expected range of construction equipment for excavation of shafts and tunnels as well as surface works;
- discussions with Central Interceptor project team on programme for the works;
- discussions with Central Interceptor project team on construction traffic expected for ingress and egress of construction yards;
- discussions with Central Interceptor project team to identify operating plant that may generate vibrations;
- site monitoring to determine background vibration levels at a number of the construction and operating access sites;
- site testing to assess Attenuation characteristics;
- identification of sensitive receivers;
- review of vibration standards and development of Project criteria;

- review of vibration database and assessment of vibration levels expected to be generated by construction works and operating plant;
- assessment of likely effects on receivers including Effects of Distance from vibration generating sources;
- assessment of mitigation measures;
- outline of Vibration Management Plan for construction and operations.

fig 1.1

2 Central Interceptor project

The overall concept proposed for the Central Interceptor is a gravity tunnel from the Western Springs area to the Mangere WWTP with various link sewers and connecting pipelines connecting the existing network to the main tunnel at key locations along this route.

The key elements of the project include:

- An approximately 13 km long 4.5 m diameter main tunnel from Western Springs to Mangere WWTP, up to 110 m below ground.
- Four link sewers connecting the main tunnel to the existing sewerage network.
- Associated connections to existing sewers including 16km of tunnels and trenched pipelines with access shafts on the CSO collector ranging from 15 m to 48 m.Associated structures at key sites along the route and at connections. At each site facilities include access shafts, drop shafts, and flow control structures. Grit traps, air intakes, air vents, or air treatment facilities are proposed at some sites.
- A limited number of overflow structures in nearby watercourses to enable the safe discharge of occasional overflows from the tunnel.
- A pump station located at the Mangere WWTP.
- Other associated works at and in the vicinity of the Mangere WWTP, including a rising main to connect to the WWTP and an emergency pressure relief structure to enable the safe discharge of flows in the event of pump station failure.

The main tunnel, link sewers, connection pipes and many of the associated structures will be underground. The tunnel and link sewers will be constructed by tunnelling methods, with access provided from around 19 surface construction sites. These surface construction sites include:

- Three primary construction sites (at Western Springs, May Road and Mangere WWTP);
- 16 secondary construction sites to provide connections to the main tunnel and link sewers.

The primary construction sites will be used for launching or retrieving the tunnel boring machine and materials for tunnel construction would be delivered and stored, tunnel spoil removed and permanent facilities constructed. Activities at the secondary sites on the main tunnel will include shaft sinking and the construction of surface facilities and at the link sewer sites will also include launching or retrieving the microtunnel boring machine.

Other construction activities include removal of vegetation, service relocations, establishment of construction yards, lay down areas and site accessways, traffic management, earthworks and site reinstatement.

The duration of construction will range from generally around 5 to 6 years at the primary sites, and 6 to 18 months at the secondary sites. Due to the nature of construction at the secondary sites the total period of occupation will be longer than this (ranging between 2 and 5 years) with some periods of time where no active construction works will occur at the sites.

The project has been developed to a concept design stage. It is likely that some details may change as the project moves through the detailed design process. Detailed construction method will be determined following appointment of a construction contractor.

The general project arrangement is shown in the AEE-Main Drawing Set. It shows the main tunnel of the Central Interceptor, the connector (link) tunnels and CSO pipes as well as the locations of the key sites for shafts and structures. The main tunnel will be excavated with a gravity fall from Western Springs at an RL starting at about RL-12m and ending at the Mangere WWTP at RL-22m. The main tunnel route currently includes 2 alignment options for the section from Kiwi Esplanade to Mangere Pump Station (WS3).

The primary (potential) launching and recovery shafts are located at Western Springs (WS1), May Rd (WS2) and the Mangere Pump Station (WS3). These are expected to require deep shafts of up to 25 m diameter excavated to tunnel level (25-70 m below ground level). The access shafts at the connector points on the primary tunnel will range in depth from 20-65 m, while shafts on the connector and CSO collector tunnels range from 15 m to 48 m.

2.1 Geology and Construction Ground Conditions

The geological conditions along the tunnel routes have been determined by geotechnical investigations undertaken by the Central Interceptor project team and are described in detail in the T&T report entitled "Central Interceptor Project Effect of Tunnels on Groundwater and Surface Settlement" (2012).

The developed long section along the main tunnel is shown in the abovementioned T&T report. The long section shows the East Coast Bays Formation (ECBF) underlying the full length of the route. In summary, this is a weak rock comprising interbedded sandstones and sandstones of Tertiary Age that form the basement rock over much of the Auckland urban area. At the southern (Mangere WWTP) end, a zone of Kaawa Formation weak rock has been identified overlaying the ECBF and a series of faults are inferred. Tauranga Age sediments have been deposited on the eroded rock surface during periods of fluctuating sea levels. These materials range from moderately to highly over consolidated soils with strengths that are still too hard. These in turn have been overlain by basalt lava flows and ash deposits from the series of volcanic eruptions that occurred across the Auckland Isthmus. The basalt ranges in strength up to 200 MPa (very strong). Recent sediments are found locally around Mays Road and at the Manukau Harbour crossing. Some fill has also been placed at the Mangere WWTP.The link sewer tunnels and deaeration tunnels have been located to generally be constructed within the ECBF or the overlying Tauranga Age sediments.

2.2 Description of Proposed Works

2.2.1 Main tunnel

The vertical alignment of the main 4.5m diameter tunnel has been located to remain in ECBF along the route, maintaining clearance beneath the strong basalt lava flows and remote from any known volcanic vents. On the southern side of the Manukau Harbour, the geology is more complex as shown on detail in Figure 2.4. The tunnel route may encounter ECBF with coarser grained fractions and some faulting is inferred. The upper surface of the Kaawa Formation is also present and the tunnel will extend into the Tauranga Group soils which are logged as Puketoka Formation. All these materials are relatively low strength and tunnelling equipment will generally be equipped with soft ground cutting tools for these conditions.

2.2.2 Link sewers

The link tunnels are expected to be excavated within weak ECBF rock. They will generally be 2.4 diameter except for a section from May Rd where the tunnel will be 4.5m diameter. The tunnels are not expected to encounter strong basalt rock but may locally approach the interface with the Tauranga Group Sediments.

2.2.3 Deaeration tunnels

These short tunnels connect the drop shafts to the main tunnels and are to be constructed at main tunnel level. Tunnel conditions for all these tunnels are expected to be ECBF rock except at Pump Station 23 (AS6) where Puketoka Formation may be present. Thrusting methods may be used for this connection.

2.2.4 Shafts

A range of shafts are to be constructed at each access point extending from the surface to tunnel level. Dimensions range up to 25 m in widest dimension for the working shafts. A series of drop shafts are also proposed for the connections to the existing network. The shafts for the link tunnels will generally be smaller ranging up to 10m.

The geological conditions expected to be encountered by the shafts on the main tunnel and link tunnel alignments is highly variable and are summarised in Table 2.1. Conditions for excavations range from recent alluvium to very strong basalt rock.

Table 2.1: Shaft Locations, Details and Expected Geological Conditions

	Location	Shaft types	Ground conditions approx. base depth b.g.l. (m)					
			Depth to tunnel invert	Fill/recent Alluvium	Basalt / tuff	Tauranga Group	Kaawa Formation	ECBF
WS1	Western Springs	WS, DS	27	3	16			8
AS1	Mt Albert Mem Reserve	AS, DS	38		11	18		9
AS2	Lyon Ave	AS, DS	45	2	5	17		19
AS3	Haverstock Rd	AS, DS	50	2	3	6		39

AS4	Walmsley Park	AS	67	4	10?	8?		45?
WS2	May Rd		70	5	8?	5?		52?
AS5	Keith Hay Park	AS, DS	80	5?				75?
AS6	Belfast Res	AS, DS	28	3				25
AS7	Option A - Kiwi Esplanade	AS, DS	28	4	11	10		3
	Option B – Ambery Park	AS	32		12	15		5
WS3	Mangere Pump Station	WS	32	26				6
L1S1	Motions Rd	AS, DS	21		2	?		19
L1S2	W.Springs Depot	AS	23	5	3			15
L2S1	Rawalpindi Rd	AS	28					28
L2S2	Norgrove Ave	AS	30			4		26
L3S1	PS25	AS, DS	28			12		16
L3S2	Miranda Res	AS	30			10		20
L2S3	Whitney St	DS	45	5				43
L3S4	Dundale Ave	AS	39	8				31
L3S5	Haycock Ave	DS	42					42

WS – Working Shaft; DS – Drop Shaft; AS – Access Shaft

2.2.5 Shallow connections to existing networks

A series of connections are required between the existing network and the new Central Interceptor works. These are shown on the AEE-Main drawing set and are summarised in Figure 1.1. The connection works will involve a range of methods including trenching, micro-tunnelling and above surface bridging.

Micro-tunnelling is proposed at WS1, beneath Gt North Rd, where depth to tunnel is about 24m and tunnelling will be in ECBF.

The trenching works also varies greatly in depth with inverts up to 8 m bgl. Ground conditions are variable but generally located within soft sediments or ECBF except at Western Springs, Mt Albert War Memorial Reserve and Lyon Ave where basalt rock is close to the surface. At Mt Albert War Memorial Reserve the proposed works include a deep trench extending up to 8 m to pipe invert.

2.3 Other Structures

A number of other shallow underground structures are proposed. These include diversion chambers, manholes, control chambers, and grit traps. These are generally relatively shallow structures which will be excavated within soft sediments or ECBF. Exceptions will be the control chamber at Mt Albert War Memorial Reserve (AS1) which will be fully excavated in basalt rock at the base of the chambers at Western Springs (WS1) and Lyon Ave.

3 Construction methodology and construction plant requirements – sources of vibration

The methods of construction and types of plant selected will have a major impact on the level of vibrations generated by the work. The following provides a general overview of construction methods that will enable an appreciation of expected vibrations. This is based on experience of tunnelling methods used in the Auckland region. Details of the plant used will vary somewhat from these projects.

The work has been considered in three phases of construction. The first phase involves establishment and construction of access shafts for the main tunnel equipment. The second phase will include excavation of the main tunnel and link tunnels as well as construction to the deaeration tunnels. Phase 3 will involve completion of the drop shafts, CSO collector pipelines, excavation of trenches and shallow structures, installation of plant and commissioning of the works.

3.1 Shaft and manhole excavation

The methods of shaft excavation will vary depending on the size and depth as well as the geology. Small diameter shafts for small pipelines and manholes up to 2-2.5m may be constructed using pile boring equipment. This will be relatively rapid and generate low levels of vibration that attenuate rapidly.

Larger shafts will require alternative methods that are expected to involve construction of a secant pile, diaphragm wall, or sheet pile retention rings to support the ground through the upper zones of soft sediments. Where basalt is encountered, the ground is expected to be initially supported by rock bolting and shotcrete while excavation will be undertaken using either rock breakers or blasting methods. Excavation of the basalt is expected to be the principal cause of vibrations in most of the shaft areas. This will include vibrations from drilling, blasting and rock breakers. Beneath the basalt, the Tauranga Group and ECBF will be excavated by conventional excavators and the latter will be supported by bolting and shotcrete. Some additional support may be necessary for the Tauranga Group soils and this may include additional perimeter piling works. Removal of spoil during construction of the shafts is expected to be by craneage.

3.2 Main tunnels

The main tunnels are expected to be constructed using Earth Pressure Balanced tunnelling machines (EPBM), of larger diameter but similar to the machines used for the recently completed Hobson Bay and Rosebank Sewer tunnels. These machines successfully excavated in materials similar to those expected in the Central Interceptor tunnels.

The operation of these machines in ECBF and Tauranga Group Sediments is expected to generate low levels of vibrations below perception levels for most people. However, some sensitive receivers may detect regenerated (also called reradiated or structure-borne) noise which is caused when continuous vibrations excite the structure of the dwelling and is detected as a hum. This will be addressed by the noise assessment report.

Other potential significant sources of vibration from the tunnel operations may include the use of rolling trains for spoil removal and transporting of lining segments, staff and equipment to the face. The use of conveyors is generally found to be low vibration generators but they may become a source if vertical conveyer or muck bucket systems are used to remove spoil at the shafts. The alternative use of craneage methods for removal of spoil and for transporting plant, people and materials to the tunnel level may also generate varying levels of vibrations.

3.3 Link Sewers

Micro-tunnelling methods are expected to be used for excavation of the smaller link (connector) tunnels. Where the tunnels extend beyond about 1400 m intermediate shafts have been provided. The micro-tunnelling methods are expected to generate low levels of vibration with the most significant levels being limited to materials and plant handling at the shaft locations.

3.4 Deaeration tunnels

These short tunnels will be most likely constructed by directional drilling or small excavators with bolting and shotcreting for temporary support until final lining is constructed. These tunnels are at the same depth as the main or connector tunnels and vibration levels are expected to be low.

3.5 Phase 3 Ancillary works

The phase 3 works are principally at the surface at the shaft locations. This involves construction of underground chambers, connection pipelines constructed in trenches and other structures.

In most cases the excavations required will be in soft sediments or residual soils. Conventional excavation plant will be used but retention works may also require construction of walls and may include driving of sheet piling or bored piles.

Basalt rock is expected to be encountered for the phase 3 works at Western Springs Depot, Mt Albert War Memorial Reserve, Lyon Ave and Motions Road. Excavation is likely to utilise rock breakers but, where deep excavations of up to 8 m into basalt are required, as at Mt Albert War Memorial Reserve, the use of blasting may be necessary.

4 Vibration criteria

4.1 Vibration Standards

A number of Standards are applied for vibrations generated by construction activities and operation of equipment in NZ. These standards are applied to limit the discomfort or impact on well-being of occupants of nearby properties as well as provide protection from damage of structures. A summary of the relevant standards is provided below.

4.1.1 Human Response Standards

The principal physiological effect standard that has historically been applied in New Zealand was NZS/ISO 2631-2:1989 "Evaluation of human response exposure to whole body vibration – Part 2: Continuous and Shock Induced Vibrations in Buildings (1 to 80 H_z)". The standard provided factored curves for vibration limits for activities based on time of day, duration as well as level of potential impact on receivers. The combined direction peak velocity curves are reproduced in Appendix A, together with the evaluation criteria. The criteria corresponds to a ppV of about 0.3 mm/s for continuous vibrations during the day (curves 2-4), which is at perception levels, while 5-10 mm/s is recommended for transient events (curves 30-90). The recommended limits are provided to ensure that receivers are not subject to significant discomfort. The limits are above perception levels, particularly the higher limits recommended for daytime activities, but they should not result in disturbance and are about 10% of the levels likely to cause fatigue or affect health.

ISO2631-2:1989 was easily applied and was included in a number of District Plans including Auckland City Isthmus and Manukau District Plans. It was particularly useful as it provided ranges of magnitudes ranging from sensitive conditions to circumstances where short term activities and well informed receivers could permit increased vibration limits. These higher levels would be clearly perceptible but ensure they should not cause unacceptable levels of discomfort to receivers. The Standard was superseded in 2003 by an informative Standard which contains no vibration criteria. This standard was subsequently withdrawn by Standards NZ but has continued to be referenced by Councils.

BS6472-2:2008 Guide to Evaluation of Human Exposure to Vibration in Buildings, Blast Induced Vibration includes similar criteria for vibration to ISO2631:1989 but its application is limited to blasting. A separate standard applies to other activities (see below). It is also noted that the criteria for human response in these standards are closely aligned to the building damage criteria, see Section 4.1.2 below.

The British Standard BS 5228-2:2009 "Code of Practice for Noise and Vibration Control on Construction and Open Sites – Part 2 Vibration- Annex B" contains human response Standards, see Table 4.1 The criteria are set to avoid adverse comment and are therefore generally lower than BS6472-2:2008. They correspond closely to the low range in the ISO2631 Standard. It is therefore puzzling why the standards have varied from the more broadly applied ISO2631 criteria.

Table 4.1: BS 5228-2:2009. Guidance on effects of vibration levels

Vibration level	Effect
0.14 $mm.s^{-1}$	Vibration might be just perceptible in the most sensitive situations for most vibration frequencies associated with construction. At lower frequencies, people are less sensitive to vibration.
0.3 $mm.s^{-1}$	Vibration might be just perceptible in residential environments.
1.0 $mm.s^{-1}$	It is likely that vibration of this level in residential environments will cause complaint.
10 $mm.s^{-1}$	Vibration is likely to be intolerable for any more than a very brief exposure to this level.

BS6472-1:2008 “Guide to assessing the human susceptibility impacts of vibration from traffic and intermittent events” adopts an entirely different approach to its companion standard for blasting. It utilises an index known as vibration dose value (VDV) which is frequency weighted and dependent on the amplitude of the event relative perception levels, the frequency of occurrence and time of day.

The following formula is used to determine vibration dose

$$VDV_{b/d,day/night} = \left[\int_o^T a^4(t)dt\right]^{0.25}$$

Where VDV b/d day/night is the vibration dose (value in $m/s^{1.75}$)

b/d is the weighting curves for vertical (b) or horizontal (d) vibration

a(t) is the frequency weighted acceleration (in m/s^2)

T is the total period of the day or night (in s) when vibration can occur.

Table 4.2 shows vibration dose ranges that might result in probability of adverse comment within residential buildings. For offices and workshops, increased factors of 2 and 4 apply respectively to the dose value ranges for a 16 hour day.

An estimate of VDV may be obtained from the following

eVDV = 1.4 a(rms) $xt^{0.25}$

Table 4.2: Vibration Dose Values for Residential Buildings ($m/s^{1.75}$) as given by BS 6472-1:2008

Place and Time	Probability of Adverse Comment		
	Low	Moderate	High
Residential Building (16 hour day)	0.2 to 0.4	0.1 to 0.8	0.8 to 1.6
Residential Buildings (8 hour night)	0.1 to 0.2	0.2 to 0.4	0.4 to 0.8

This Standard has been applied on several roading projects in NZ but the Norwegian Standard NS8176E is generally more favoured. The Norwegian Standard NZ8176 E:2005 "Vibration and Shock – Measurements of Vibrations in Buildings from Land based Transport and Guidance to Evaluation of its Effects on Human Beings" has been applied on recent NZTA projects including operating traffic for the Waterview Connection consents conditions. This standard specifically addresses vibration induced by transport, including road traffic. The performance criteria are given in Table 4.3.

Table 4.3: Dwelling Classification and the Likelihood of Moderate to High Annoyance

Type of Vibration	Class A 8%	Class B 10%	Class C 15%	Class D 25%
Statistical Maximum Value for Weighted Velocity V_w, 95 (mm/s)	0.1	0.15	0.3	0.6
Statistical Maximum Value for Weighted Acceleration A_w, 95 (mm/s)	3.6	5.4	11	21

The majority of residences are expected to be Class C receivers in terms of the standards criteria which applies to new (transportation) infrastructures. This corresponds to conditions where about 15% of affected persons will be disturbed by the levels of vibration but less than 15% will experience discomfort. This Standard is widely used for roading but is not applicable over the full range of activities for this project.

4.1.2 Application of Human Response Standards

Our experience is (as expected for such experience based Standards), there is little difference in the levels of recommended vibrations to avoid adverse comment between the human response Standards. Most standards, however, do not provide for an increase in permitted levels of vibration if the work is undertaken in accordance with a well developed management plan that recognises that some minor discomfort may be acceptable by receivers provided close controls are implemented. This includes good communication and notification and, if necessary mitigation to assure receivers they are not at risk. Only the BS6472-2:2008 and ISO2631:1989 Standards provide for this. The former standard only applies for blasting.

For ease of application, as well as reference to the existing District Plans, ability to apply to a range of activities, and ability for the public to readily understand the criteria, we prefer the ISO 2631:1989 Standard for at least the construction phase. If it is not acceptable to utilise this superceded standard, we would recommend use of the BS6472-2:2008 Standard for blasting and BS5228-1:2009 for other activities but note that the latter is more restrictive where high levels of control are provided. This BS5228-1:2009 standard may also be used for operational vibrations but we note that BS6472-1:2008 is being promoted by CIRIA (2011) in the UK and CIRIA has a strong influence on construction practice in NZ.

4.1.3 Building Damage Standards

The Standards addressing susceptibility of damage to buildings invariably reference work undertaken by Siskind et al (1980) as the basis for setting criteria. They applied probabilistic methods to damage threshold from blasting. This work is summarised in Table 4.4 and shown on Figure 4.1.

Table 4.4: Vibration Damage Threshold (mm/s) after Siskind et al (1980)

Damage Type	Probability %			
	5	10	50	100
Threshold for cosmetic damage e.g. cracking of untapped plaster joints	13	18	64	228
Minor Damage: loosening of plaster and hairline cracks in plaster, and in masonry around openings	46	56	127	406
Onset of structural damage affecting load support elements	64	76	152	430

The CIRIA (2011) guidelines recommend that extrapolation of the data be undertaken to reduce the probability of damage (due to transient events) with a confidence limit greater than 95%.

The standards have adopted factors applied to these thresholds to limit the potential for damage to acceptable levels. The most commonly used Standard for structural damage is the German standard DIN 4150-3:1999 “Structural Vibration – Part 3: Effects of Vibration on Structures”. The DIN 4150 guidelines for vibrations are summarised in Table 4.5 and shown in Fig 4.2. They include guidelines for residential buildings together with criteria for both commercial/ industrial buildings and high sensitivity structures. The guidelines provide for increased levels of vibration as the wave frequency increases, recognising that structures will generally have increased response in the low (1 to 10Hz) range. Conversely, the body has increased sensitivity at increased frequency which tends to cap the level of vibration able to be tolerated for construction activities.

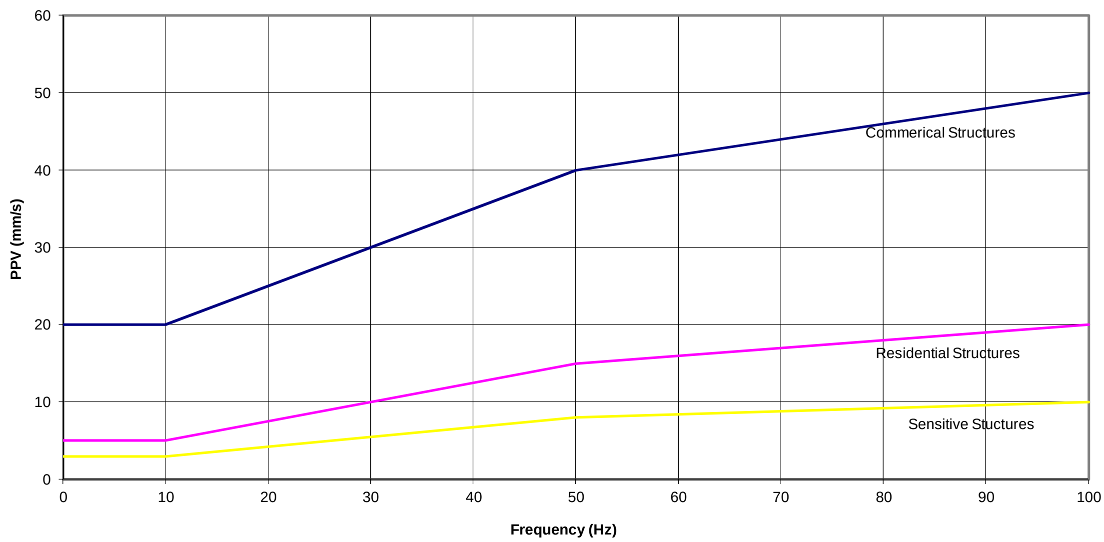
Table 4.5 Guideline values of vibration velocity, for evaluating the effects of short-term vibration, DIN4150-3:1999

Line	Type of Structure	Vibration Velocity (mm/s)			
		Foundation Frequency			Plane of Floor of Uppermost Storey
		Less than 10 Hz	10 to 50 Hz	50 to 100* Hz	Frequency Mixture
1	Buildings used for commercial purposes, industrial buildings and buildings of similar design	20	20 to 40	40 to 50	40

2	Dwellings and buildings of similar design and/or use	5	5 to 15	15 to 20	15
3	Structures that, because of their sensitivity to vibration, do not correspond to those listed in lines 1 and 2 and are of great intrinsic value (eg buildings that are under a preservation order)	3	3 to 8	8 to 10	8

* For frequencies above 100Hz, at least the values specified in this column shall be applied

Figure 4.2 Baseline Curves Representing Short-Term Vibartion Effects to Structures in Relation to Recorded Data



For continuous (steady state) levels of vibration DIN 4150-3:1999 recommends a limit of 5mm/s as measured in the plane of the uppermost storey be applied to all buildings other than Category 3 (sensitive or high intrinsic value) structures.

The use of statistical design approaches for developing construction methods is being increasingly used for management of vibrations. There are clear benefits in applying best practice methods to blasting and other activities that generate significant levels of vibrations that may impact on adjacent properties. Where works are undertaken to a well developed methodology and management plan, staff are well trained, outcomes are monitored and results analysed to assess statistical parameters, then the designs can be targeted closer to the limits. This rewards good practice by reducing cost, controlling risk and generally achieving a better outcome for both the project and receivers. The application of the method is described further in Section 6.3.

The AS2187.2-2006 “Explosives - Storage, Handling and Use” cites more conservative guideline values from British Standard (BS) 7385-2 *Evaluation and measurement for vibration in buildings; Part 2: Guide to damage levels from ground-borne vibration* for cosmetic and minor structural damage to residential and commercial structures. Table 4.6 presents vibration criteria for commercial and residential buildings.

Table 4.6: BS7385-2 Transient vibration guide values for cosmetic damage[1]

Type of Building	Peak component particle velocity	
	4Hz to 15Hz	15Hz and above
Reinforced or framed structures. Industrial and heavy commercial buildings	50 mm/s at 4Hz and above	
Unreinforced or light framed structure. Residential of light commercial type buildings	15 mm/s at 4Hz increasing to 20 mm/s at 15Hz	120 mm/s at 15Hz increasing to 50 mm/s at 40Hz and above

Note 1: Reproduced from Appendix J of AS2187.2:2006

While this standard is widely referenced in New Zealand for storage, handling and monitoring methods for works using blasting methods, the DIN 4150:1999 criteria is the most widely applied guidelines for vibrations limits. The accepted use of statistical design methods with this standard also favours its application for this project. It should be noted, however, that lower limits may apply for highly sensitive plant such as some hospital and laboratory equipment.

5 Current Operative District Plans

The Auckland Council District Plan (Manukau Section) includes a rule for vibration, Rule 5.18.4.1, to ensure vibration from a business activity does not cause significant nuisance. This rule requires that "at or within the boundary of any adjacent site zoned for residential, Papakainga or Maori Purpose" no activity shall create vibration exceeding the following average levels.

Vibration Performance Standards		
Time	Maximum Weighted Vibration Levels (Wb or Wd)	
Monday to Saturday 7.00 am to 6.00 pm	0.045 m/s^2	1.0 m/s^2
At all other times	0.015 m/s^2	0.05 m/s^2

The weighted vibration levels W_b and W_d shall be measured according to BS6841:1987 and measurements are to be obtained at any point where it is likely to affect the comfort or amenity of persons occupying an adjacent site or where damage is the primary concern, measurement is to be undertaken on the ground near the building. The District Plan also references the ISO 2631-2 Standard but considers it is not suitable as it was a draft Standard at the time of preparation of the Plan.

The Auckland Council District Plan (Auckland City Isthmus Section) addresses vibrations arising from blasting in Section 8.8.2.7 for Development Controls for Business 7, 7A and 7B Zones. In Clause 8.8.2.7(a) it requires "the Peak Particle Velocity should not exceed the limits set out in Table 1 of DIN 4150 Part 3:1986." (This is the same as DIN 4150 - 3: 1999 as included in Table 4.5). The District Plan qualifies the above requirement in Section 8.8.2.7(e) as follows.

"Notwithstanding 8.8.2.7(b) above, blasting activities undertaken at Mt Wellington Quarry and Three Kings Quarry and any extensions of these quarries shall be conducted so that 95% of the blasts undertaken (measured over any 20 blasts on the foundation of any building in the Business 7 Zone) shall produce peak particle velocities not exceeding 5 mm/s and 100% of the blasts undertaken shall not exceed 10mm/s irrespective of the frequency of the blast measured." This recognises the utilisation of best practice methods by these quarries.

The District Plan also references the ISO 2631:1989 Standard in Section 8.8.3.9 where for vibrations in buildings it states in 8.8.3.9(a):

"Activities shall not generate vibrations which may cause discomfort or adversely affect the health and well being of the occupants of adjacent premises. Vibrations which do not exceed the limits, referred to below as set out in the provisions of the International Standard ISO 2631-2:1989 Evaluation of Human Exposure to whole body vibration – Part 2 Continuous and Shock Induced Vibrations in Buildings (1 to 80 H_z), will be deemed to meet this requirement."

The limits referenced in the Plan are applicable factored curves defined in Annex A and Table 2 of the Standard (included in Appendix A).

The Conditions of Consent for the Manukau Harbour Crossing Project is of relevance as they were jointly agreed in 2007 by the Auckland and Manukau City Councils. The Conditions required a Construction Vibration Management Plan (CVMP) to be prepared. The Condition includes:

"The CVMP shall include details relating to the control of vibrations associated with all Project Works. It shall, as far as practicable, be formulated to achieve compliance with the vibration Standards of the German Standard DIN4150, and shall address the following aspects

a) Vibration monitoring measures

b) Existing vibration levels

c) Possible mitigation measures

d) Complaint response

e) Reporting procedures

f) Notification and information for the community of the proposed works

g) Where appropriate vibration testing of construction processes (eg piling) to confirm that the vibration limit will not be exceeded

h) Location for vibration monitoring when construction activities are adjacent to critical buildings

i) Operational times

j) Preparation of dilapidation reports on critical dwellings prior to, during and after completion of the works."

Also of relevance is the recent decision for the Waterview Connection Project. The Conditions of Consent require that a Construction Noise and Vibration Management plan (CNVMP) be prepared and describe the measure adopted to meet the criteria set out in Conditions CNV 1, 4, 5, 6, 8-13. These are included in Appendix B.

The Standard referenced for limiting construction vibrations was DIN 4150-3:1999. Of particular relevance was the Board's decision to permit the use of statistical methods for blasting and other construction activities such as piling, excavation, compaction and drilling provided there is no exceedance of a ppV of 10 mm/s irrespective of the frequency of the activity measured. Also of note in CNV.13 is the following advice note:

"It is accepted that the Criteria for CNVZ (Noise) and CNV.4 (Vibration) may not be met at all times, but that the NZTA will take all practical steps to achieve compliance, taking into account the hierarchy of mitigation options outlined in Condition CNV.1 (ix).

6 Assessment of vibration effects

6.1 Vibration effects and site characteristics

Ground borne vibrations are generated by oscillating motion that is transmitted by contact between particles in the ground. The vibration wave forms in the ground propagate as either compression (P) waves or shear (S) waves. The interaction of these waves with the ground surface produces Rayleigh (R) and Lowe (L) waves. The Rayleigh waves are particularly important as they generally produce the largest particle velocities which directly impact on the imposed strain in structures. Measurements of vibration for the assessment of risk to structures are therefore generally measured in terms of peak particle velocity, ppV. The human body is primarily responsive to the forces imposed on it. Hence the effect on the human body is usually measured in terms of acceleration. By assuming a regular sinusoidal wave form, the corresponding limits may be expressed in either acceleration or ppV for any given frequency.

The magnitude of the vibrations are influenced by a number of factors, the principal variables being the energy of the source and the distance to the receiver. Other variables which are generally less significant include the geology, the surface topography and groundwater.

The general prediction model that is used for propagation of vibrations with distance is:

$$ppV = k\left(\frac{D}{\sqrt{E}}\right)^{-n}$$

where k = site constant

D = distance from the source to the receiver

E = Energy of source (often expressed as Maximum Instantaneous Charge Weight (MIC) for blasting)

n = attenuation factor, primarily dependent on geology and groundwater, generally between 0.9 to 1.5 for Auckland geological conditions.

Where the energy source is constant then the equation reduces to:

$$ppV = k'd^{-n}$$

The site constants are generally determined for each activity based on trials or using experience in similar areas. The predictive models may then be utilised to assess the effects on receivers. For design it is useful to establish the confidence limits of the activities and establish a compliance approach based around these limits (e.g. for blasting design, the upper 95% confidence limit is targeted to meet the conservative recommendations of limits to protect property from minor damage). As noted above, this promotes and rewards the use of best practice in the construction industry, whereby constructors which apply high levels of quality control can benefit by targeting higher charge weights. The application of this method, together with an upper “regulatory” limit, has been accepted for the Waterview Connection Project, see Appendix C, and this is applied on many of the quarries in the Auckland region, see Auckland City District Plan 8.8.2.7(b).

A typical flow chart setting out the control systems and the response requirements for any exceedance is included in Appendix C.

6.2 Site testing

A series of site monitoring tests have been undertaken to determine background vibration levels on the tunnel alignment and to assess the typical attenuation levels for the ground. Monitoring has also been carried out to establish typical vibration levels at the Orakei pump station at Victoria Ave drop shaft to determine the effects of an operating system.

6.2.1 Background monitoring

Vibration measurements have been undertaken at 5 representative sites. These locations include:

- WS1 Western Springs Depot
- AS4 Walmsley Park
- AS6 Kiwi Esplanade
- L352 Miranda Reserve
- L354 Dundale Ave

The monitoring was undertaken with transducers located for periods close to roads which are currently the most likely source of vibrations in the area. At Western Springs the tramway was also monitored. For each location instruments were placed in close proximity to the source (1-2m) as well as at distance to provide a measure of attenuation.

Results of the monitoring are included in Appendix D and summarised in Table 6.1. They indicate the maximum source of vibrations is generally heavy vehicles, particularly buses. However, these are relatively infrequent at most sites and, while peak particle vibrations of up to 3.1 mm/s were measured close to the kerb, the level of vibration attenuated rapidly to less than 0.5 mm/s at a distance of 10 m.

The maximum level of vibrations recorded was at Walmsley Park where heavy traffic occurred at a relatively high frequency (30 HCV vehicles/hour). The monitoring site was at a low point in the road where the irregular surfacing adjacent to a pedestrian crossing caused increased levels of vibration of up to 3.1 mm/s close to the kerb. At the other sites the road surfacing was in good condition and vibration levels were generally less than 1.5 mm/s and attenuated rapidly to less than perception levels within 10 m.

At Motions Rd, where the Museum of Transport and Technology operate a tram ride, maximum recorded vibrations with a ppV of up to 9.0 mm/s were measured close to the rails. A number of events were recorded for the tram and these are summarised in Table 6.1. The attenuation relationship for these results has been analysed to determine a best fit line which can be expressed in the form.

$$ppV = 9.26(d)^{-1.44}$$

The attenuation exponent is relatively high for a site where basalt is present and may reflect the properties of the soft soils overlying the rock.

Table 6.1: Summary of Background Vibration Monitoring

Access Shaft	Location	Transducer distance from Kerb / track (m)	Peak Particle Velocity (mm/s)	Source	Notes
WS1/LISI	Motions Rd	1	9.0	Tram	Attenuation Characteristics Measured
		5	0.76		
		10	0.36		
		15	0.2		
	Motions Rd	3	0.25	Truck (6m)	
		7	-		
		12	0.19	Truck (6m)	
		17	-		
AS4	Walmsley Park (Sandringham Rd Extension)	0.5	3.09	Bus	Heavy trafficked road and irregular road surfacing (ppV exceeding 1mm/s due to heavy vehicles every 2 minutes on average)
		10	1.43		
AS6	Mangere (Kiwi Esplanade)	1	0.254	Van	Light traffic. No heavy vehicles recorded
		10	0.445		
L352	Miranda Res	1	0.445	Light Truck	
		10	0.143		
L354	Dundale Ave	1	1.46	Bus	
		10	1.01		

6.3 Blast vibrations

No site specific testing has been undertaken for blasting for the Central Interceptor Project.

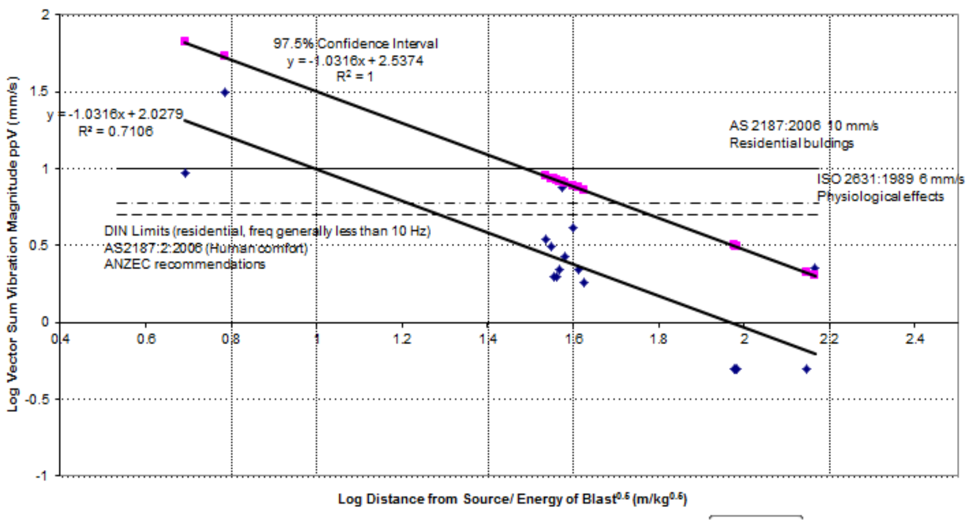
Tonkin & Taylor's database includes a number of projects where blasting of basalt has been undertaken and good records have been kept of Maximum Instantaneous Charge (MIC) and distance of monitoring from the blast. A typical set of results showing blast monitoring plotted on a log-log plot is shown in Figure 6.1. Regression analyses of results have provided indicative constants typical of basalt rock vibration characteristics. These are:

$$ppV_{mean} = 206\left(\frac{D}{E^{\frac{1}{2}}}\right)^{-1.19}$$

Results of blasting, where good control has been applied, generally achieve a statistical Standard Deviation of about 0.22-0.25. The corresponding upper 97.5% confidence limits (representing 2 standard deviations from the mean) are:

$$ppV_{97.5\%} = 345\left(\frac{D}{E^{\frac{1}{2}}}\right)^{-1.03}$$

Figure 6.1: Typical Vibration Monitoring Results for basalt rock site - Site Attenuation Characteristics and 97.5 % Confidence Interval for data



When these results are applied to achieve the 5mm/s recommended DIN4150 criteria for residential properties, with 97.5% probability of compliance, the following typical safe blasting distances are determined for MIC weights of AN60 explosive.

Table 6.2: Safe Blasting Distances (97.5% Confidence Limits)

Maximum Instantaneous Charge (MIC) kg	Design Distance (MPa)
1	61
2	86
3	106
5	136
10	193

To achieve economic blasting, alternative explosive options may need to be considered for areas where sensitive receivers or residential structures are within 80-90 m of the shafts.

The tolerance to blasting is often affected by the cumulative effect of the associated airblast pressure wave. This is a sub-audible low frequency wave that causes rattling of windows and loose ornaments. Depending on the blast design, the confinement of the blasts in the shaft may result in amplification or damping of this effect. This has been addressed further by the noise consultants.

The use of good practice blasting methods also reduces the potential for flyrock. This is often associated with poor control of drilling and loading of holes particularly where there is a free face in close proximity to the hole (lack of adequate burden). The potential for flyrock in a bottom driven shaft is very low and, if there is any potential for this, the use of blasting mats is recommended to contain the fragmented rock.

Construction planning needs to be developed around a regular programme of blasting. Experience indicates blasting at 1 to 3 blasts/day is practical and enables residents to be well prepared for the events.

Blasting often generates air pressure waves (air blast noise). These cause rattling of windows and disturbance to sensitive receivers. The effects of air pressure waves are addressed by the noise assessment. It is noted that the level of disturbance felt by people can be enhanced if the ground vibrations are accompanied by a high level of air blast noise.

6.4 Operational Vibrations

Measurements of vibration levels from operations of plant were undertaken on the Orakei Main Sewer at the Orakei Pump Station and the Victoria Ave drop shaft. The objective of this study was to assess the magnitude of vibrations that could be expected after commissioning of the Central Interceptor.

The measurements at the Orakei Domain Pump Station (PS64) were undertaken on 14 July 2011. The weather conditions had been showery. Two pumps were operating at the time of monitoring, No's 2 and 6. Monitoring was carried out with transducers mounted on the No. 2 pump casing, on the concrete floor immediately below the pump and at a location within the pump station building about 18 m laterally from the pump (approx. 25 m direct path). ppV vibration levels on the pump casing were typically in the range of 4-5 mm/s at a frequency of $43H_z$. The pumps are supported by heavy structures and the vibrations did not transmit far into the building structure with levels of about 0.14 mm/s detected immediately beneath the pump and also 0.14 at 18m from the pump. It is concluded that the levels of vibration beyond the pump station building would be imperceptible to the majority of people.

Measurements at the Victoria Ave Drop Shaft were undertaken on 14 July 2011 to assess levels of vibration from the shafts during operations. The transducer was set up on top of the shaft structure. The levels of vibration were generally low, less than 0.1 mm/s and hence are unlikely to be discernible to people beyond the shaft housing.

7 Construction vibration estimates

The works will involve the use of heavy construction methods that will utilise plant that generates vibrations at a range of levels. This section identifies the main construction activities, and associated plant, and assesses the likely effects on nearby receivers. It includes consideration of the likely magnitude of any generated vibrations, the duration of the work, the potential effects on sensitive receivers and property, as well as discusses potential mitigation measures that may be required.

It is assumed in this assessment that surface works undertaken in the initial establishment of the tunnel access works, including excavation of shafts, will generally be limited to daytime hours. The completion works, including construction of trenched pipelines and subsurface chambers, will also be limited to daytime work hours. Only work directly associated with continuous tunnelling will include night-time operations and, if necessary, this may impose limits to surface support activities such as spoil removal and material delivery.

The activity sources that are expected to be the potential generators of the highest levels of vibrations from the project are listed in Table 7.1. The table also identifies the expected distance where the recommended vibration limit criteria are likely to be exceeded. Note it does not consider effects of noise or regenerated noise.

The vibration design distance includes consideration of duration of the activities, allows for increased vibration levels for short term works such as establishment activities and the short time a property will be affected as the tunnel excavation rapidly progresses. The distances also include adopting limits that are low in the recommended range for longer activities such as shaft excavation.

This information has been used to identify those sites where the activities may require modification to normal construction practices or the use of mitigation measures, see Section 8.

Table 7.1: Safe design distances for construction activities

Work Type	Source	Ground type	Design Distance (m)		Comments
			Structures	People	
Site Establishment	Diggers, Loaders, Trucks etc	TG	3-5	5	Higher tolerance for short term access works.
	Site Buildings Construction	TG	3	3	
	Access Roadworks	TG	3	3	
Shaft Excavation – soft to hard	Diggers, Cranes, Trucks	TG	5	5	
	Piling / Diaphragm	TG / ECBF	10	20	Higher vibrations may

ground	Wall Equipment				be generated by dropping buckets to expel spoil.
	Sheetpile driving (Soft to hard ground)	Alluvium/TG/ECBF	10	15	
Shaft Excavation or trench - Hard Rock (Basalt)	Rock breaker	Av	10	15	
	Blasting	Av	Depends on MIC see Table 6.2		Need to also consider air over pressure.
	Drilling and Shotcreting	Av	10	10	
Tunnelling	EBPM	ECBF	5	10	Possibility of regenerated noise, see Noise Consultant's Report
	Micro-tunnelling	ECBF/TG	10	10	
	Small Road Header	ECBF	6	10	
	Muck Cars and TGins	-	5	10	May increase where shunting occurs
	Vertical Conveyor	-	3	5	
	Crane	-	3	5	
	Tunnel Segments Handling	-	5	10	
Surface Works	Shored Trenches and Shallow Underground Chambers	TG/ECBF	3	5	
		AV	See blasting criteria Table 6.2 - <u>OR</u>		Blasting
			10	15	Rockbreaker
	Sheetpiled Trench	Alluvium/TG/ECBF	10	15	
	Vibrating Rollers	-	10	15	Road and Site Remediation

Note: The safe design distances are based on a combination of published information, experience and the site characteristics measured. Some further information on the effects of different types of equipment is included in Appendix D. The safe distances for critical operations need to be confirmed on site. Works that need to be undertaken within these distances should also give consideration to methods and plant that could reduce generated vibrations at the source or mitigate effects.

7.1 Drop shafts

The drop shafts are expected to involve a range of construction methods dependent on ground conditions encountered. Where soft alluvial soils are present in the upper sections of the shafts, ground retention will generally be provided by contiguous piles or diaphragm walls for the large shafts or casing for the smaller shafts. These options all have potential to generate high levels of vibrations that will need to be managed to achieve the recommended vibration limits.

Basalt is present over sections of many of the shafts for the main tunnel and some of the connector tunnels.

The practical minimum charge level for blasting of basalt in the shafts may necessitate either liaison with closest receivers on regular exceedance of the recommended limits for vibration or use of alternative low energy explosives to fragment the rock.

Below the basalt, excavation will be in Tauranga Group or ECBF. This will be undertaken with conventional excavation plant with support provided by Shotcreting and bolting. The vibration levels experienced by the closest receivers from these works is expected to be below perception levels.

The thickness of basalt in a number of the shafts is likely to require the use of blasting to fragment the rock and enable removal of the rocks. The alternative use of rock breakers is likely to be limited to thin zones of basalt as it will be slow and increase the level of disturbance due to the continuous noise and vibrations.

The effects of blasting can be controlled by using best practice methods which limit the number of blasts to regular times, provide good notice of blasting, use decked charges with measured Maximum Instantaneous Charge Weights (MIC) per delay, electronic detonators and careful monitoring to enable changes to be made if geology varies.

7.2 Main tunnelling works

The main tunnels are expected to be excavated using an Earth Pressure Balance Machine (EPBM). In the ECBF weak rock this equipment will generally produce low level vibrations that would be expected to attenuate quickly and be below the perception threshold within 10 m for most people. The main tunnel is generally at a depth of over 25 m so there is unlikely to be any vibration effects from boring. The rate of excavation is also expected to be high, averaging over 10m/day. The time that any sensitive receiver would be subject to any vibration is therefore very short.

Associated with tunnelling is the potential for regenerated noise. This is caused by low levels of vibration that are transmitted into the building structure and sets up a low level humming noise that may cause nuisance (but not structural damage). The potential effects of regenerated (structure-borne) noise are addressed by the noise consultant.

The installation of the segmented lining will provide a number of potential sources for vibration. The delivery and handling of segments at the surface will need to be managed to limit impacts on neighbours. It is expected that vibrations from this source if well managed should attenuate below accepted levels within 5-10 m.

The segments will be transferred to the face on rail carriages. These heavy concrete sections may cause vibrations if the rail is not well maintained, otherwise the levels of vibration should be below perception within 10-15m. Similarly it is expected the operation of the segment erector should generate vibrations that are below perception within 10 m.

The removal of spoil will be by muck wagon or conveyor. If the former is utilised the largest potential for vibrations are from poorly maintained rail joints and shunting of the wagons. Operations need to be carefully managed and maintained to limit these effects over the duration of the works.

7.3 Link Sewer

The microtunnelling equipment expected to be used for the smaller link sewer tunnels will generate low levels of vibrations during excavation. The depth of cover is reduced for some sections of these tunnels but at the ground surface, as these are smaller machines, it is unlikely that significant vibrations will be experienced from the excavation. The potential for regenerated noise may still be significant, however, the rate of tunnelling progress would mean that any effects would be of a short duration.

The installation of the precast tunnel lining or pipe sections is by launching from the jacking pits. This is a low vibration source process. The handling of the heavy precast sections may result in a level of generated vibrations from the lifting equipment, delivery vehicles and on site transporters. It is expected the levels of vibrations generated by this equipment will be below perception level within 10 m.

7.4 Trench and underground structures excavation (excluding drop structures)

The excavation of trenches for shallow pipelines and underground structures will generally encounter soft soil conditions at most of the sites. Conventional diggers may be utilised for these earthworks and shields or retention works may need to be mobilised to achieve stable excavations.

These operations generally generate low levels of vibrations except for driving and removal of sheet piling where a clearance of 10 m is typically required to achieve damage vibration standards. If the work is extended beyond several days physiological criteria for vibrations may also need to be met.

The excavations for trenched pipelines and underground structures are expected to encounter basalt rock in a number of locations. These include Western Springs (WS1), Mt Albert War Memorial Reserve (AS1), Lyon Ave (AS2), Kiwi Esplanade (AS7), Motions Rd (L1S1) and Western Springs Depot (L1S2). Basalt rock may also be found within the depth of excavations in May Rd (WS2).

Where the remaining depth of basalt to be excavated is small, less than 2 m, rock breakers are expected to be utilised. Generally a set back distance of 15 m will ensure vibration limits for damage are achieved. If the duration extends beyond several days, the physiological criteria may also impact on the works.

7.5 Other works

The primary cause of vibrations from other works will be the operation of heavy vehicles delivering heavy equipment, tunnel segments or pipes and removing tunnel spoil. The levels of vibrations generated by such operations are highly dependent on the condition of the access roadways. The background monitoring undertaken as part of this study on nearby roadways determined that vibration levels generated by trucks operating on city roads, was generally less than 2mm/s at a distance of 2 m from the source and attenuated rapidly to below 0.5 mm/s within 10 m. If the roadway is not well maintained or includes a sharp bump, as was present at the pedestrian crossing on Sandringham Rd Extension, the levels of vibration can increase markedly.

The operation of cranes, hoists and conveyors can all contribute to levels of vibrations but these are generally small and should not exceed the recommended limits beyond the working areas.

Maintenance works during operations will also require access and use of trucks, pumps and other plant. Vibration levels from this equipment will need to be controlled within normally applied vibration criteria.

8 Mitigation options

It is expected that works will be designed to be undertaken to comply with vibration limits proposed for the project. However, construction processes contain inherent risks such that the targeted vibration levels are not always achieved. This requires that a margin of safety is provided in the target levels for "outlier" conditions. Where monitoring of activities is undertaken that enables the distribution of vibration levels generated, a statistical approach may be adopted to provide a high level of confidence that limits will not be exceeded. A requirement for 95% compliance with the limits of DIN 4150:1990 has been recommended as a suitable criterion. This means that construction methods that adopt best practice and exercise a high level of control of activities will benefit by utilising higher target vibration levels while activities which have lower levels of control or singular events need more conservative target levels to ensure compliance.

It is noted that the recommended control limits also include an upper "regulatory" limit for vibrations which, if exceeded, triggers activation of a response procedure which is designed to ensure there are no repeats of unplanned events. A flow chart demonstrating how this is applied is included in Appendix C.

This requires that the cause of any exceedance of consented levels is investigated and changes are made in the methodology where practicable to address the magnitude of vibrations generated by the source.

If full compliance with the vibration criteria cannot be achieved by modifying the method, it may be necessary to consider other methods to reduce the effects. These could include:

- communication with adjacent affected residents
- coordination with residents to carry out works when they are likely to be out
- use of an alternative method of construction with reduced vibration effects
- isolation of the source e.g. use of elastic or rubber packers beneath rails over critical section of rail
- construction of a vibration attenuation barrier between the source and receiver, e.g. excavation of a trench (depth at least half the wavelength of the transmitted vibrations (Rayleigh) wave form), installation of a barrier or series of piles or open holes to "interfere" with the transmission of the vibrations
- where other mitigation is not feasible, possible temporary relocation of residents during the activity where it is close to property
- modification of the affected building structure to change the response characteristics e.g. installation of bracing to modify the building response frequency
- isolation of very sensitive equipment such as utilising an airbag or floating slab.

It is noted that the recommended standards include substantial margins to limit the risk of damage and no structural damage is likely within a distance of half that given in Tables 6.2 and 7.1.

9 Consideration of sensitive receivers and potential for damage to neighbouring properties

An initial assessment of the effects on adjacent properties of vibrations generated by construction and operations of the project has been undertaken. This has involved review of the likely construction methods, the levels of vibration that they will generate and estimation of the distances where vibration levels will exceed the proposed limits for both structural damage and sensitive receivers.

A summary of construction activities and safe distances for vibration design has been provided in Table 7.1. This is based on the expected distance required to achieve the proposed vibration limits. Table 9.1 sets out an assessment of potential vibration effects on neighbouring properties. A list of properties most affected by the construction vibrations is provided in Table 9.1. The risk of vibrations impacting on residents or structures has been assessed for the critical activities according to the following criteria:

- Low Risk – May be perceptible to residents but should not cause disturbance. Risk of damage less than minor
- Moderate Risk – May cause minor discomfort and should be acceptable for limited periods. No risk to health. Minor risk of cosmetic damage to dwellings but no risk of structural damage. Condition surveys of closest structures recommended.
- High Risk – May be acceptable to receivers for occasional short term events. Likely to cause significant discomfort if vibrations are continuous. Minor risk to health to sensitive receivers and may require relocation. Moderate risk of cosmetic damage but low risk of damage to structural elements. Condition surveys of all potentially affected structures recommended.
- Very High Risk – Potential risk to health and relocation recommended. Significant risk to sensitive structures. Condition surveys of all structures and application of mitigation measures recommended.

Generally the effects of vibration on these properties can be managed by control of construction methods to limit vibration levels at the source. However, where the works are to be undertaken over a short period and there is low risk of structural damage, there is the option to also consult with residents on a level of acceptable exceedance. If necessary, other mitigation measures may also be considered, see Section 8.

Table 9.1: Design safe distances for specific properties

Location	Properties closest to proposed works	Distance to dwellings	Risk of Damage/ Disturbance without mitigation	Notes	Potential Mitigation Options	Residual Effect Post Mitigation
WS1 Western Springs	MOTAT	140 m	Very Low[1]	Blasting of shafts and underground chambers in basalt rock (also shaft in basalt proposed 20m from commercial property south side of Great North Rd and 60 m from MOTAT)	Nil, Monitor	Less than minor
	42 Sefton Ave 3 Bullock Track	120 m	Very Low		Nil, Monitor	Less than minor
AS1 Mt Albert Memorial Park	65 Asquith Ave (2 rear dwellings)	15 m	High to very high	Deep trench in basalt, blasting of thick layer of basalt in shaft	Hydraulic rock breakers & limited use of blasting operated within Din 4150	Minor. No damage to structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.
	9 - 17 Wairere Ave	30 m – 50 m	Moderate	Blasting of shaft	Small charge weights to limit blasting vibrations to within Din 4150	Minor, some disturbance to residents
	9 Wairere Ave	10 m	Very High	Deep trench in basalt	Hydraulic rock breakers & limited use of blasting operated within Din 4150	Minor. No damage to structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.

Location	Properties closest to proposed works	Distance to dwellings	Risk of Damage/ Disturbance without mitigation	Notes	Potential Mitigation Options	Residual Effect Post Mitigation
AS2 Lyon Ave	11-27 Morning Star Place	15 m	High	Trenching and blasting of shafts in basalt	Hydraulic rock breakers & limited use of blasting operated within Din 4150	Minor, no damage to structures but likely disturbance to residents which can be mitigated through measures as described in Section 8.
	12-28 Morning Star Place	40 m	Moderate	Trench in basalt	Hydraulic rock breakers & limited use of blasting operated within Din 4150	Minor
	1 Wagener Pl	30 m	Moderate	Blasting of shafts in basalt	Small charge weights to limit blasting vibrations to within Din 4150	Minor, some disturbance to residents
	15 Lyon Ave	15 m	Mod. - High	Trench in basalt	Hydraulic rock breakers & limited use of blasting operated within Din 4150	Minor. No damage to structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.
AS3 Haverstock Rd	98 Haverstock Rd	40 m	Low	Possibility of thin zone of basalt in shafts	Small charge weights to limit blasting vibrations to within Din 4150	Less than minor
	7 Camden Rd	50 m	Low		See above	Less than minor
AS4	3 O'Donnell Ave	20 m	High		Small charge weights to	Minor. No damage to

Location	Properties closest to proposed works	Distance to dwellings	Risk of Damage/ Disturbance without mitigation	Notes	Potential Mitigation Options	Residual Effect Post Mitigation
Walmsley Park					limit blasting vibrations to within Din 4150	structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.
	5-9 O'Donnell Ave	33 m	Moderate		See above	Minor
WS2 May Rd	51a Marion Ave	25 m	Mod - High	Large 20m diameter shaft. Risk dependent on extent of basalt in shafts	Small charge weights to limit blasting vibrations to within Din 4150	Minor. No damage to structures but disturbance possible to residents
	53a-55a Marion Ave	20 m	Mod - Very High		Small charge weights to limit blasting vibrations to within Din 4150	Minor. No damage to structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.
AS5 Keith Hay Park	20 & 22 Gregory Pl	-	N/A	Purchase and remove dwellings		
	19 Gregory Pl	12 m	Low	Secant piles to ECBF	monitor	Less than minor
	18 Gregory Pl	16 m	Low		monitor	Less than minor
AS6 Manukau	6/41 Fredrick St	20 m	Moderate	Secant piles to ECBF. New	Small charge weights to	Minor. No damage to

Location	Properties closest to proposed works	Distance to dwellings	Risk of Damage/ Disturbance without mitigation	Notes	Potential Mitigation Options	Residual Effect Post Mitigation
Harbour				dwelling	limit blasting vibrations to within Din 4150	structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.
	52a Frederick St	40 m	Low			Less than minor
AS7 (Option A - Eastern Route) Kiwi Esplanade	Trench - Kiwi Esplanade, Yorkton Rise, Muir Ave, Villa Court	5-20m	Low to high	Shallow Trench in basalt	Hydraulic rock breakers & limited use of blasting operated within Din 4150	Minor. No damage to structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.
	85 - 89 Kiwi Esplanade	120 m	Low	Blasting of Shaft in basalt	Nil, Monitor	Less than minor
AS7 (Option B - Western Route) Ambury Park	Trench – Ambury Rd, Muir Ave, Villa Court)	5-20m	Low to high	Shallow Trench in basalt	Hydraulic rock breakers & limited use of blasting operated within Din 4150	Minor. No damage to structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.
	20, 26 Andes Ave	65m	Low	Blasting of shaft in basalt	Monitor and limit vibrations to DIN 4150	Minor. No damage to structures but some disturbance to residents

Location	Properties closest to proposed works	Distance to dwellings	Risk of Damage/ Disturbance without mitigation	Notes	Potential Mitigation Options	Residual Effect Post Mitigation
						which can be mitigated through measures as described in Section 8.
WS3	Mangere Pump Station	>200m	Low	Large Diameter shaft in weak materials	Nil, monitor	Less than minor
L1S1 Motions Rd	100-102 Motions Rd Western Springs College	140 m	Low	Rock Breaker or blasting of thin layer of basalt rock	Hydraulic rock breakers & limited use of blasting operated within Din 4150	Less than minor
	Auckland Zoo[2]	50m	Moderate		Hydraulic rock breakers & limited use of blasting operated within Din 4150	Minor. No damage to structures but minor disturbance possible to residents and animals
L1S2 Western Springs Depot	WS Depot – Buildings	20 m	Mod - High	Blasting of basalt in shaft	Small charge weights to limit blasting vibrations to within Din 4150	Minor. No damage to structures but disturbance likely to residents which can be mitigated through measures as described in Section 8.
L2S1 Rawalpindi Reserve	19 Rawalpindi	37 m	Low	ECBF, secant piles to ECBF	Nil, monitor	Less than minor
	17 Rawalpindi	30 m	Low		Nil, monitor	Less than minor
L2S2 Norgrove Ave	16 Norgrove Ave	12 m	Mod - High	ECBF, high potential to disturb residents by piling	Piling equipment operated to limit vibrations to within	Minor. Low risk of vibration damage, piling closest to

Location	Properties closest to proposed works	Distance to dwellings	Risk of Damage/ Disturbance without mitigation	Notes	Potential Mitigation Options	Residual Effect Post Mitigation
				works	DIN4150	dwelling likely to result in some disturbance to residents
	14 Norgrove Ave	15 m	Moderate		Piling equipment operated to limit vibrations to within DIN4150	Minor. Low risk of vibration damage, piling closest to dwelling likely to result in some disturbance to residents
	27 Verona Ave	12 m	High		Piling equipment operated to limit vibrations to within DIN4150	Minor. Low risk of vibration damage, piling closest to dwelling likely to result in some disturbance to residents
L3S1 Pump Station PS25	30a Miranda Pl	55 m shaft	Low	Secant piles to ECBF. (New dwelling)	Nil, monitor	Less than minor
	3/28 Taylors Close	40 m Chamber	Low	ECBF	Nil, monitor	Less than minor
L3S2 Miranda Reserve	353 Blockhouse Bay Rd Units	50 m	Low	Secant Piles to ECBF	Nil, monitor	Less than minor
	373 Blockhouse Bay Road	27 m	Low-Moderate		Piling equipment operated to limit vibrations to within DIN4150	Minor
	356 East side of	30 m	Low		Piling equipment operated	Minor

Location	Properties closest to proposed works	Distance to dwellings	Risk of Damage/ Disturbance without mitigation	Notes	Potential Mitigation Options	Residual Effect Post Mitigation
	Blockhouse Bay Rd				to limit vibrations to within DIN4150	
L3S3 Whitney St	124 Whitney St	22 m	Low - Moderate	6 m ϕ shaft, Secant Piles to ECBF	Piling equipment operated to limit vibrations to within DIN4150	Minor
	128 Whitney St	15 m	Moderate - High (disturbance)		Piling equipment operated to limit vibrations to within DIN4150	Minor. Low risk of vibration damage, piling closest to dwelling likely to result in disturbance to residents
	130 Whitney St	15 m	Moderate - High (disturbance)		Piling equipment operated to limit vibrations to within DIN4150	Minor. Low risk of vibration damage, piling closest to dwelling likely to result in disturbance to residents
L3S4 Dundale Ave	66D Dundale Ave	30 m	Low	2.4 m ϕ shaft (cased hole ?),	Piling equipment operated to limit vibrations to within DIN4150	Less than minor
	68-78 Dundale Ave	50m	low	Preschool facility	Nil, monitor	Less than minor
L3S5 Haycock Ave	2 Haycock Ave	6m	High	Secant piles to ECBF rock	Piling equipment operated to limit vibrations to within DIN4150	Minor. Low risk of vibration damage, piling closest to dwelling likely to result in disturbance to residents
	4 Haycock Ave	-	N/A. House			

Location	Properties closest to proposed works	Distance to dwellings	Risk of Damage/ Disturbance without mitigation	Notes	Potential Mitigation Options	Residual Effect Post Mitigation
			to Be Removed			
	6 Haycock	3m	Very High		Piling equipment operated to limit vibrations to within DIN4150	Minor. Low risk of vibration damage, piling closest to dwelling likely to result in disturbance to residents
	79b White Swan Rd	25 m	Low		Piling equipment operated to limit vibrations to within DIN4150	Less than Minor
Tunnels[3]		>20m	low	Excavation in ECBF (see note 2)	Monitor. Machine expected to	Less than minor, short period of perceptible vibrations

Note 1. The vibration levels generated by the MOTAT tram are expected to exceed transmitted vibrations from construction works at the Western Springs site (WS1).

Note 2. The potential for disturbance to animals in the zoo has previously been considered by Tonkin & Taylor during an assessment of effects for the MOTAT tram. This study concluded that animals in zoos adjust quickly to levels of vibration which are below human perception levels (about 0.3mm/s). Most would also not be highly alarmed by low frequency events which transmit vibrations up to 1mm/s such as blasting. The effects of air blast noise would also need to be considered.

Note 3. The depth of the tunnels generally exceeds 20m. It is concluded the risk of damage to dwellings due to tunnelling beneath the properties is less than minor. The levels of vibrations should not cause disturbance to people but may be perceptible to sensitive receivers, particularly if also associated with regenerated noise. The tunnelling excavation will progress rapidly (about 10-20m/day) and the short period of any felt effects are not expected to result in any significant discomfort. Intermittent higher levels of vibration may be generated by tunnel support activities such as shunting of muck wagons, handling of segments, etc. These activities will need to be managed to limit vibrations, particularly if these are undertaken regularly at the same locations.

10 Construction Vibration Management Plan

It is recommended that a construction vibration management plan (CVMP) identifying the minimum standards be prepared to be complied with during the works. These will be designed to minimise the effects on health and limit discomfort to people as well as ensure the risk of damage to structures is less than minor.

The CVMP is recommended to include the following:

- Vibration criteria for the project
- Hours of operation for construction activities likely to generate significant levels of vibrations
- List of plant that is likely to generate significant levels of vibration
- Requirements for vibration monitoring including trials for establishing attenuation characteristics and the associated statistical parameters for design of safe operating distances
- Requirements for condition (dilapidation) surveys on potentially affected properties prior to, during and after completion of the works
- Requirements for background vibration monitoring in advance of the works
- Notification and information for the community
- Reporting requirements including response flow chart identifying actions and reporting protocols in the event of any exceedences
- Roles and responsibilities of key personnel on site including contact details and qualifications of staff responsible for handling, design and use of explosives
- Procedure for storage, handling and use of explosives on the project
- Construction operator training procedures for activities likely to generate significant levels of vibrations
- Construction vibration mitigation options, and
- Recording system for receiving and handling of complaints.

11 Applicability

This report has been prepared for the benefit of Watercare Services Ltd with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose without our prior review and agreement.

Tonkin & Taylor Ltd

Environmental and Engineering Consultants

Report prepared by: Authorised for Tonkin & Taylor Ltd by:

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Peter J Millar

Senior Geotechnical Consultant

PJM/mcs

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